Research Trends in Physics: Inertial Confinement Fusion

La Jolla International School of Physics, The Institute for Advanced Physics Studies, La Jolla, California

Recirculating Induction Accelerator as a Low-Cost Driver for Heavy Ion Fusion

J.J. Barnard, M.A. Newton, L.L. Reginato, W.M. Sharp, H.D. Shay, and S.S. Yu

University of California
Lawrence Livermore National Laboratory
Livermore, CA 94550

As a fusion driver, a heavy ion accelerator offers the advantages of efficient target coupling, high reliability, and long stand-off focusing. While the projected cost of conventional heavy ion fusion (HIF) drivers based on multiple beam induction linacs are quite competitive with other inertial driver options, a driver solution which reduces the cost by a factor of two or more will make the case for HIF truly compelling. The recirculating induction accelerator has the potential of large cost reductions. For this reason, an intensive study of the recirculator concept was performed by a team from LLNL and LBL over the past year. We have constructed a concrete point design example of a 4 MJ driver with a projected efficiency of 35% and projected cost of less than 500 million dollars. A detailed report of our findings during this first year of intensive studies has been recently completed (Ref. 1).

Point Design Parameters

A 4 MJ driver was chosen for our point design. The driver requirements, as set by the target and reactor, are given in Table 1. Our point design consists of three rings, the largest of which is approximately 2 km in

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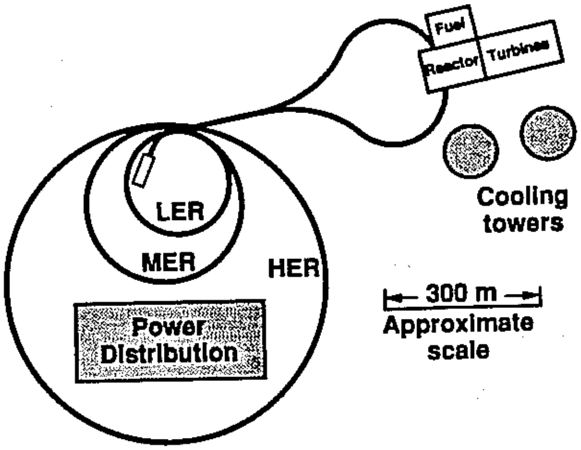
Table 1: Adopted Parameters Set by Target and Reactor Considerations

Total Pulse Energy	4 MJ
Final Heavy Ion Energy	10 GeV
Heavy Ion Atomic Mass	200
Charge State of Heavy Ions	+1
Total Electrical Charge in Ion Pulse	400 μC
Main Pulse Duration at Target	10 ns
Target Stopping Range	.15 gm cm^{-2}
Final Spot Radius on Target	1.5 mm
Final Normalized Emittance	.001 cm-rad
Final Momentum Spread	.004
Repetition Rate	10 Hz
Accelerator Efficiency x Target Gain	$\geq$ 10
Accelerator Efficiency	$\geq$ .20
Power Plant Lifetime	30 years

circumference. The overall layout is as shown in Fig. 1. Each ring consists of repeated periods (half-lattice-periods) consisting of quadrupole focusing magnets, dipole bending magnets, and accelerating gaps. The parameters for these elements are shown in Table 2.



	LER	MER	HER
Beam energy (GeV)	0.003–0.05	0.05–1.0	1.0–10.0
Beam pulse duration (μs)	200–30	30–2.5	2.5–0.25
Number of laps	100	100	100
Number of beams	4	4	4
Circumference (m)	700	923	1976

LER — Low enery ring
MER — Medium energy ring
HER — High energy ring

Figure 1

Table 2

	LER†	MER†	HER†
Ion Energy(GeV)	.003 - 05	.05 - 1	1 - 10
Pulse Duration (μs)	200 - 30	30 - 2.5	2.5 - .25
Circumference (m)	700	922	1976
Current/Beam (A)	.5 - 3.5	3.5 - 40	40 - 400
No. of beams	4	4	4
No. of laps	100	100	100
Pipe radius (m)	.078	.064	.061
Half-lattice period (m)	.85	1.56	3.5
Residence Time (ms)	16.2	4.7	3.1
Induction modules			
Inner radius (m)	.3	.25	.24
Outer radius (m)	.45	.55	.36
Length (m)	.4	.85	.89
No. of cores	786	546	1060
Bends (normal dipole magnets)			
Length of dipole (effective) (m)	.31 (.15)	.54 (.41)	1.27 (1.15)
Maximum Magnetic Field (T)	.9*	.85	.81
No. of dipole magnets per beam	670	450	480
Combined Function Superconducting magnets			
Length of quadrupole (effective)(m)	.47 (.23)	.92 (.73)	1.94 (1.76)
Maximum quadrupole field (T)	2.0	1.25	1.0
Maximum dipole bias field (T)	N/A*	.75	1.0
No. of magnets per beam	786	550	536

*LER does not utilize combined function quadrupole magnets

†LER, MER, and HER are abbreviations for low-, medium-, and high-energy ring respectively.

Cost Scaling

The recirculating induction accelerator is a circular machine in which several ion beams are made to traverse induction cores repeatedly over 50 to 100 laps. By means of time-varying dipole fields, the beams are confined within the same pipes from lap-to-lap, even though the beam energy is continually increasing. In this configuration, the induction cores, pulsers and focusing magnets are reused many times. This feature drastically reduces the quantity of components required, in comparison to a linear machine where each component is used exactly once per shot. In particular, the total induction-core cross-section is inversely proportional to the number of times the cores are reused on each ion bunch.

The size of a recirculator is roughly determined by the bending radius of the heavy ions. Thus, in an average magnetic field of about 0.6 Tesla, the circumference of the machine is ~2 km/q, for a 10 GeV mass A = 200 heavy ion of charge state q. This is in contrast to the linear machine, the length of which is determined by the maximum accelerating gradient of about 1 MV/m/q, leading to a length of ~10 km/q.

In addition to the accelerator length scalings, there are also advantages in terms of the overall transverse dimensions of the recirculator with even greater cost impact. In a recirculator, the same amount of charge could be accelerated at much lower currents and longer pulses. The core costs associated with the longer pulses are more than offset by the reductions due to recirculation. The lower currents allow designs with fewer beams and much lower focusing fields. The net result is that by comparison, recirculators have much smaller transverse dimensions than their linear counterparts.

Since the costs of the HIFSA designs (Ref. 2) of the linear machine are predominantly in cores, quadrupoles, structure and pulsers, it is evident that the cost of the recirculator has the potential for being significantly less than for a linear machine. Large reductions in the overall cost of the driver could be realized as long as the savings in the quantity of cores, pulsers, and focusing magnets are not offset by the need for bending magnets, time-varying dipole pulsers, and high repetition rate induction core pulsers. By means of concrete point designs, we have demonstrated that such is indeed the case.

Driver Efficiency

A circular induction driver requires the introduction of time-dependent dipole fields. The field energy stored in the dipoles around a ring is

$$e_D = \frac{BR^2\,[B\rho]\,N_b}{\mu_0/4\pi}$$

where B is the average dipole field, R the pipe radius, $[B\rho]$ the rigidity of the heavy ion, and N_b the number of ion beams. In our design example, this field energy is about 10 times larger than the total beam energy of 4 MJ. Fortunately, it is possible to design dipole pulser systems where most of the energy is recovered. A pulser system employing a sinusoidal ringing circuit was evaluated and the calculated energy recovery was as high as 95%. A first laboratory prototype test at low level already yields over 90% recovery.

In addition to energy recovery, we have also introduced a DC component to the bending field by adding supplementary superconducting dipoles. This reduces the stored energy in the time-dependent component to roughly a quarter of the total field energy in our design examples. This combination of bending field strategies led eventually to dipole losses which were quite acceptable.

The extra energy expenditure incurred by the introduction of dipoles is more than compensated for by the savings in induction core losses resulting from the much smaller cores in recirculators. This could be seen from a formula derivable from empirical data on core losses in Metglas (Ref. 3). The ratio η of core loss to beam energy gain for ion beam with total charge Q (in μC) and pulse duration τ (in μs), traversing a Metglas cell of inner radius R_i (in m) and outer radius R_0 (in m), with induced flux swing ΔB (in T), is given by

$$\eta = 437\,\frac{(\Delta B(T))^{2/3}\,(\tau(\mu s))^{1/3}\,(R_0(m) + R_i(m))}{Q(\mu C)}$$

The important thing to note is that this ratio is linearly proportional to the transverse dimension, but varies as only a cube root of pulse length. Hence, from the efficiency point of view, there are substantial advantages in going to small cells.

Technical Issue

The concept of recirculating induction accelerator is not new. Indeed, elements of recirculation were mentioned in some of the earliest HIF workshop proceedings. Nevertheless, as a serious driver candidate, the heavy ion recirculator is novel with no known precedent. The closest identification to existing machines would be a hybrid between an induction linac and a very fast synchrotron. The design of such a machine is constrained by a unique set of physics and technology issues. Among these are: (1) the high repetition rate of the induction pulsers; (2) the energy recovery requirements on the ramped dipole magnets; (3) the long residence time constraints on the beam current density and on the vacuum, which must be obeyed to minimize beam loss due to beam-beam charge exchange and to stripping by residual gas, respectively; and (4) constraints arising from the beam dynamics of space-charge dominated beams in ring geometry. In the last category, the central issue is to keep the growth of beam emittance to an acceptably low level by careful design of beamlines. Abrupt transitions in the beamline, particularly in the extraction and injection processes, and errors in magnets and pulsers, must be minimized.

The required induction pulser repetition rates for our point designs are in the range of 15 to 50 kHz. Since the speed of the ions increases continuously, the repetition rate varies from lap to lap. In addition, pulses are continuously compressed from ~ 200 μs at 3 MeV injection to ~ 200 ns at 10 GeV extraction. Hence, the pulse format must be capable of variations from lap to lap. The field effect transistors (FET) have capabilities consistent with these requirements, and were adopted as the switches of choice for our point design. The actual performance of these switches in the setting of an integrated experiment is a critical issue for the success of the recirculator concept. Likewise, while conceptual solutions have been constructed for the dipole pulsers, the actual performance characteristics (jitter, control of time dependence, energy recovery, etc.) have yet to be demonstrated.

Beam ions can be lost by beam-beam charge exchange as well as by stripping due to collisions with the background gas. On the basis of available data, beam loss can be kept to about 10% over the residence times (of few milliseconds). However, there are still large uncertainties in some of the basic data on stripping and ionization cross sections, as well as the desorption and sputtering coefficients for heavy ions impinging upon the beam pipes.

In terms of the beam dynamics, the key issue is emittance growth. All simulations and analytic calculations up to this point, as well as our first beam-around-bend experiment, have not shown inordinate emittance growth for well designed beamlines. Our first evaluations of alignment requirements indicate that with steering, magnet errors of ~100 μ are acceptable. Longitudinal debunching of the beam due to space charge are controllable with special "voltage ears" incorporated into our point design. The longitudinal instability, which is a critical issue for the linac version, is much milder for the recirculator because of a much lower accelerating gradient. Likewise, the transverse instability (Beam Breakup Instability) as well as the resonance crossing instability have been shown to be insignificant in our point design. The extraction and injection beamlines for the recirculator have been designed, using a number of large rectangular quads and dipole kickers (~ 10 μs risetime). Up to this point, we have not encountered any insurmountable beam dynamics issues. More detailed theoretical calculations and computations, as well as prototype experiments, will be necessary to establish the physics of the recirculator concept.

Cost Model

Our cost and efficiency estimates were made on the basis of a bottom-up approach. The costs of the magnets are normalized to existing machines, since they require little extrapolation in technology. For several other

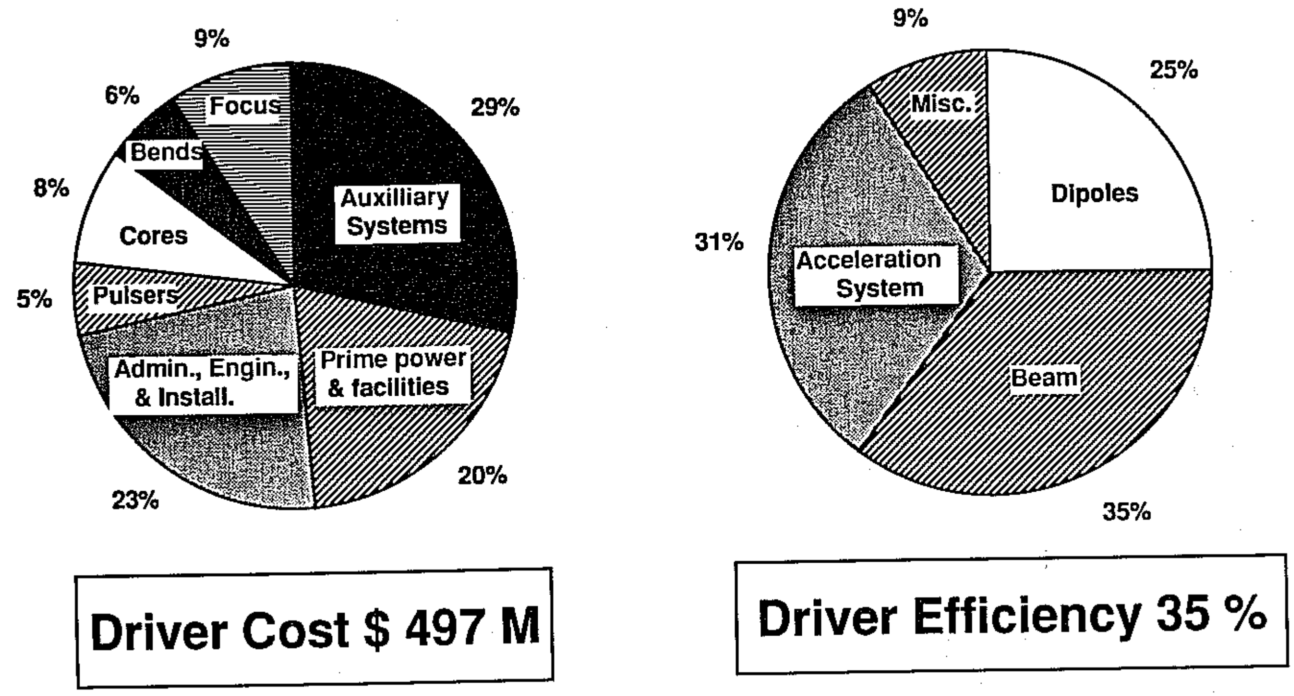


Fig. 2. Cost and efficienct estimate of 4 MJ recirculating induction driver point design.

components we have made some assumptions about cost reductions based on development of manufacturing technologies taking place in the next 30 years or so. In particular, we assume that core material (Metglas) could be reduced to $5 per kilogram (factor of 3 reduction from present costs), and that the cost of FET's can be reduced to 12¢/kW (reduction of 4 from present costs).

The cost and efficiency breakdown for the point design are shown in Fig. 2. We note that the high technology components (induction core, focusing and bending magnets) account for roughly one third of the total cost. The remainder are in the prime power, conventional facilities administration and engineering and various auxiliary systems including the injector, alignment, control, the injection and extraction systems, vacuum, and the final focus system. The efficiency includes all losses in pulsers and cores, dipoles, refrigeration, vacuum, etc., and is projected at 35%.

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